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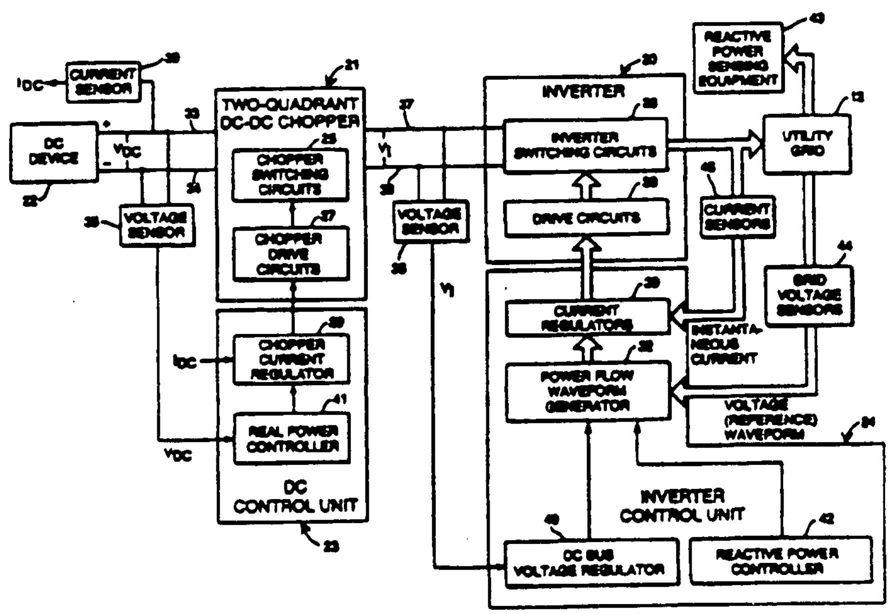
(54) Title: GRID CONNECTED BI-DIRECTIONAL CONVERTER INCLUDING A PWM, DC-DC CHOPPER, AND ENERGY STORAGE/SUPPLY DEVICE

(57) Abstract



A bi-directional converter (i.e., AC- > DC or DC- > AC) for transferring electrical energy between a high voltage AC power grid (12) and a DC energy storage/supply (22) (such as a battery or a series of photovoltaic or fuel cells). The converter includes a PWM inverter (20) coupled to the grid (12), and a DC-DC chopper (21) coupled between the PWM inverter (20) and a DC energy storage/supply (22). The PWM inverter (20) includes a switching circuit (26) having high speed electrical switches arranged in pairs coupled between the AC grid phase voltage rails and DC-DC chopper voltage rails. An inverter control unit (24) includes a DC bus voltage regulator (40) to regulate the voltage on the DC side of the PWM inverter (20), and a reactive power controller (42). A DC control unit (23) includes a real power controller (41) that controls the real power flow by controlling the current flow of the DC energy storage/supply (22). By modulating the DC switches (25) in the DC-DC chopper (21), the DC current to the DC energy storage/supply (22) is controlled to provide a desired real power flow through the DC-DC chopper (21), independent of the voltage (VDC) of the energy storage/supply (22).

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GRID CONNECTED BI-DIRECTIONAL CONVERTER INCLUDING A PWM, DC-DC CHOPPER, AND ENERGY STORAGE/SUPPLY DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

Cross-reference is made to the following commonly-assigned, copending patent applications:

"A Controlled Electrical Energy Storage Apparatus for Utility Grids", Serial No. 07/986,798 filed on December 8, 1992;

"Static Reactive Power Compensator", Serial No. 07/800,643 filed on November 27, 1991, now U.S. Patent No. 5,187,427, issued February 16, 1993;

"Variable Speed Wind Turbine with Reduced Power Fluctuation and a Static VAR Mode of Operation", Serial No. 07/799,416 filed on November 27, 1991, now U.S. Patent No. 5,225,712, issued July 6, 1993;

"Low-Noise Power Bus", Serial No. 07/728,112 filed on July 10, 1991, now U.S. Patent No. 5,172,310, issued December 15, 1992

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates generally to conversion technologies for converting electrical energy between AC and DC. The present invention is particularly useful for connecting an electrical utility to an apparatus that stores and/or produces DC electrical energy.

Description of Related Art

Electrical utilities generate and distribute electrical energy in its AC form. Because storage of AC electrical energy is difficult and costly, utilities usually generate power continuously so that it is available on demand. However, if the some of the AC energy is not used, then the resultant excess electrical generation is wasteful.

In its DC form, electrical energy can be stored in well-known and cost effective devices such as batteries or fuel cells. DC electrical energy can also be produced by photovoltaic cells. Energy storage technologies which produce or store electrical energy in DC form

require a power inverter to exchange energy with an AC utility system. Such a inverter could include a power electronic AC-DC rectifier and/or DC-AC inverter coupled between the AC utility system and the energy storage device such as that described in Serial No. 07/986,798 cross-referenced above, which is a pulse-width-modulated (PWM) voltage-fed inverter that can transfer power bidirectionally.

Advantageous characteristics of PWM power inverters include low harmonic distortion of output current, controllable line power factor, and the capability to operate satisfactorily over a wide range of utility source impedances. However, in order to maintain the advantageous operating characteristics of a PWM inverter, the voltage on the DC side of the inverter must be greater than the peak-to-peak line-to-neutral voltage on the AC side of the inverter.

Maintaining a DC voltage high enough to meet this requirement can be difficult for at least two reasons: 1) the DC voltage decreases with the battery's charge and 2) certain DC generation and storage technologies have practical limits to their operating voltage, which can result in undesirably low AC output voltages when such voltage-fed inverters are used to interconnect them to a high voltage utility system. Low AC interconnection voltages are undesirable in that they are accompanied by high AC currents, which require higher equipment ratings, as well as voltage transformation to match the utilization voltage. Further, higher currents result in lower overall system efficiency.

It would be an advantage to provide an effective and practical AC-DC conversion system that provides higher AC output voltages, but requires a relatively lower DC voltage within the limits of a practical and cost-effective DC generation or storage system.

SUMMARY OF THE INVENTION

The present invention allows a DC-AC inverter to be used with a DC device having a lower voltage than that required by the DC side of the inverter.

The power conversion system includes a pulse-width modulated (PWM), voltage-fed inverter coupled to a utility AC source, a two-quadrant DC-DC chopper inverter coupled to the PWM inverter,

and a DC device coupled to the DC-DC chopper. The power conversion system bidirectionally controls the flow of power through the inverter and the DC-DC chopper. First, a real power flow is selected in direction and amount. The current flow through the DC-DC chopper is controlled by pulse-width modulation techniques to provide the selected current, thereby controlling the real power flow. The DC-AC converter is controlled by an inverter control unit, responsive to a sensed voltage on its DC side to maintain a predetermined voltage on said DC side. The inverter control unit includes a DC bus voltage regulator that controls the DC voltage V_i on the DC side of the inverter by regulating the instantaneous current flow with pulse width modulation techniques to import or export power from the utility grid in an amount necessary to maintain a predetermined optimal voltage V_i^*. The inverter control unit also includes a reactive power controller to control reactive power flow between the inverter and the utility grid. Real power flow through the inverter is only controlled indirectly by controlling the real power flow through the DC-DC chopper to the DC device.

The DC-DC chopper includes a pair of transistors that are operated in complementary fashion with the appropriate duty cycle to provide an operator-specified DC current through a filter inductor and through the DC device in direction and amount. A DC control unit controls real power by controlling the DC current flow through the DC-DC chopper to the DC device.

The DC bus voltage regulator controls the DC side of the DC-AC inverter at its optimal level and as a result, an AC output voltage may then be provided even with a relatively low DC voltage at the DC device because the DC voltage of the DC device is decoupled by the DC-DC chopper from the AC output voltage of the voltage-fed inverter. The DC control unit uses the DC-DC chopper to control current flow with the DC device. For example, if a battery is used on the DC side, the DC-DC chopper is used to control the current flow to and from the battery, and the DC-AC inverter is unaffected by the state of charge of the battery, as long as a minimal voltage is provided. If the DC device is a photovoltaic or fuel cell generating device, then the DC-

AC inverter will be operable even at low DC voltages. The inverter is useful for a DC electrical energy apparatus for an electrical grid, as well as for any other DC-AC coupler that has a high AC voltage relative to the DC device.

In both the charge and discharge modes, the maximum line-to-line RMS AC voltage required to produce sinusoidal current waveforms on the AC side of the inverter is $[(\sqrt{3} \times V_i) \div 2\sqrt{2}]$. Without the DC-DC chopper-type inverter, the maximum line-to-line RMS AC voltage required on the utility side to produce sinusoidal current waveforms on the AC side of the inverter to the utility is known to be $[(\sqrt{3} \times V_{Battery}) \div 2\sqrt{2}]$. Therefore, with the DC-DC chopper, the DC inverter voltage V_i is substituted for the battery voltage V_{DC} and sinusoidal current can be produced even though the battery voltage is lower than would otherwise be required.

In addition to controlling the flow of real power, the power flow control unit can operate the inverter to supply reactive power to the grid for compensation of reactive power loads. Specifically, the power flow control waveform may be shaped to provide a specific reactive power, either as a specific number of VARs (Volt-Ampere Reactive units), or as a power factor angle which defines the relation between the real and reactive power supplied to the grid. The reactive power supplied by the inverter helps the grid to compensate for the reactive loads commonly placed on the grid by consumers of electricity.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram illustrating a DC electrical energy apparatus including a DC device, a four-phase inverter, a utility grid, power generating facilities, and electrical power users.

Fig. 2 is a block diagram of a DC electrical energy apparatus including a two-quadrant DC-DC chopper.

Fig. 3 is a schematic diagram of a preferred embodiment of the DC electrical energy apparatus including a two-quadrant DC-DC chopper.

Fig. 4 is a flow chart illustrating formation of a power flow control waveform within the power flow control unit.

Fig. 5 is a diagrammatic illustration of a preferred embodiment of a power flow waveform generator.

Fig. 6 is a flow chart illustrating operation of a charge controller for the real power controller.

Fig. 7 is a block diagram of a real power controller that provides the DC device current control waveform for the chopper.

Fig. 8 is a block diagram of a delta modulator current controller for controlling inverter currents in accordance with the power flow control waveform.

Fig. 9 is a block diagram illustrating an inverter having its DC side coupled to a DC bus that is coupled to a first DC-DC chopper and a first DC device such as a battery, and also coupled to a second DC-DC chopper and a second DC device such as a photovoltaic cell.

DETAILED DESCRIPTION OF THE INVENTION

Figs. 1 through 9 of the drawings disclose various embodiments of the present invention for purposes of illustration only. One skilled in the art will readily recognize alternative embodiments of the structures and methods illustrated herein that may be employed without departing from the principles of the invention.

Reference is made to Fig. 1 which is a block diagram illustrating a DC electrical energy device 10 connected to an AC electric power grid 12. The AC electric power grid 12 includes transmission lines and other electrical transmission circuits commonly provided by electrical utilities. Power for the AC electric power grid 12 is supplied by power generating facilities 14, which may include any of a number of conventional generating facilities, for example coal-fired plants, nuclear plants, and hydroelectric plants. The AC electric power grid 12 provides power to electrical power users 16. The power users 16 include any of a wide range of consumers of electricity, for example a household or a large factory.

In the DC electrical energy apparatus 10, a four-phase inverter comprising a three-phase voltage fed inverter 20 and a two-quadrant DC-DC chopper 21 are coupled between the AC electric power grid 12 and a DC device 22. The DC device 22 may comprise any DC device

that stores or produces DC electrical energy. For example, the DC device 22 may comprise a battery that stores DC electrical energy at selected times and releases energy back at other times, in a manner as will be described. Alternately, the DC device 22 may comprise a DC energy generating device such as a photovoltaic cell array. A DC control unit 23 is coupled to the DC-DC chopper 21 and the DC device 22 to control real power flow, as will be described.

The three-phase voltage-fed inverter 20 includes circuits for converting electrical energy from AC to DC, or from DC to AC (i.e., the inverter 20 is bidirectional). An inverter control unit 24 controls the inverter 20 to control the flow of power therethrough. The inverter control unit 24 receives inputs from sensors coupled to the AC electric power grid 12, including the voltage on the grid 12 and the instantaneous current flow between the inverter 20 and the grid 12. The inverter control unit 24 also receives a voltage V_I on its DC side. Responsive thereto, the inverter control unit 24 controls the flow of power through the inverter 20. Furthermore, the inverter control unit 24 can control the inverter 20 to supply reactive power to the electric power grid 12.

Real power flow through the inverter 20 is bidirectional: the real power flow can be in either direction, including a charge direction from the AC electric power grid 12 to the DC device 22, or a discharge direction from the DC device 22 to the AC electric power grid 12. In the charge direction, electrical energy on the AC electric power grid 12 will be stored in the DC device 22 which could occur when the power supplied by the generating facilities 14 exceeds the needs of the power users 16. In the discharge direction, energy from the DC device 22 supplies power to the AC electrical power grid 12. The discharge direction would be selected when the power needs of the AC electric power grid 12 exceed the supplies available from the power generating facilities 14, or if it is simply more economical to provide energy from the DC device 22 instead of the power generating facilities 14.

The AC electric power grid 12 may supply 3-phase power at 480 volts rms, which is typical of the utilities in the United States.

However any other polyphase power supply or power grid may utilize the DC electrical energy apparatus 10.

Reference is now made to Fig. 2 which is a detailed block diagram of the DC electrical energy apparatus 10. The inverter 20 includes inverter inverter switching circuits 26, described in more detail with reference to Fig. 3. The inverter switching circuits 26 are driven by conventional inverter drive circuits 28 selected to satisfy the requirements of the inverter switching circuits 26. The inverter drive circuits 28 are controlled by current regulators 30 illustrated in the inverter control unit 24. The current regulators 30 are described in more detail with reference to Fig. 9. The inverter control unit 24 also includes a power flow waveform generator 32 described in further detail below, for example with reference to Figs. 3, 4, 5, 6, and 7.

The two quadrant DC-DC chopper 21 includes circuits described in more detail with reference to Fig. 3 that control DC current flow between the DC device 22 and the DC side of the inverter 20. The chopper 21 includes chopper switching circuits 25 driven by conventional chopper drive circuits 27 selected to satisfy the requirements of the chopper switching circuits 25. The chopper drive circuits 27 are controlled by chopper current regulators 29, which are described in more detail with reference to Fig. 9.

The DC device 22 is coupled between a +DC rail 33 and a -DC rail 34. A voltage sensor 35 is coupled to sense the voltage V_{DC} across the +DC rail 33 and the -DC rail 34. The sensed voltage V_{DC} typically varies with the charge stored in the DC device 22, and is useful to control storage of electrical energy.

An additional voltage sensor 36 is coupled to sense a inverter voltage V_i across a +rail 37 and a -rail 38 of the DC bus between the inverter switching circuits 26 of the inverter 20 and the DC-DC chopper inverter 21. A current sensor 39 is coupled to measure a DC current flow I_{DC} in direction and amount through the two-quadrant DC-DC chopper 21. The current I_{DC} is useful for controlling the real power flow through the chopper 21, as will be described in more detail with reference to Figs. 5, 6, and 7. A DC control unit 41 is coupled to the

chopper current regulators to control the DC current between the DC device 22 and the inverter 20.

The inverter control unit 24 includes a DC bus voltage regulator 40 and a reactive power controller 42 described in more detail with reference to Figs. 5, 6, and 7 coupled to the power flow waveform generator 32 to control the direction and amount of power flow through the inverter 20. The DC bus regulator 40 controls the DC bus voltage V_i by importing or exporting real power from the utility grid 12 in the amount necessary to maintain a constant DC bus voltage V_i. The inverter control unit 24 also includes a reactive power controller 42 coupled to the power flow waveform generator 32 to supply a selected reactive power flow between the inverter 20 and the utility grid 12. The amount of reactive power flow is selected responsive to a reactive power measurement sensed by conventional reactive power sensing equipment 43 coupled to the utility grid 12. The reactive power controller 42 is described in more detail below with reference to Fig. 5.

The voltage on each line of the utility grid 12 is sensed by grid voltage sensors 44, for example by voltage transformers, and supplied to the power flow waveform generator 32 as a voltage (reference) waveform. Additionally, current sensors 46 sense the instantaneous current flowing on each of the phase lines coupled between the inverter 20 and the utility grid 12. The instantaneous current amounts are supplied to the current regulators 30 to aid in controlling the current flow through each of the phase lines.

Reference is now made to Fig. 3 which is a schematic diagram of the DC electrical energy apparatus 10. The DC-DC chopper 21 includes a first DC switch 47 and a filter inductor 48 coupled in series on the +rail 37 between the inverter 20 and the DC device 22. The first DC switch 47 is coupled to one of the inverter drive circuits 28, to control its switching. The inverter drive circuits 28 are in turn controlled by the power flow waveform generator 32. The DC-DC chopper 21 also includes a second DC switch 49 coupled to a node 51 defined between the first DC switch 47 an the filter inductor 48. Specifically, the second DC switch 49 is coupled between the node 51 and the -DC rail 34. The second switch 49 is driven by chopper inverter

drive circuits 27, which is in turn controlled by the DC control unit 23. The first DC switch 47 and the second DC switch 49 operate together as a pair. Specifically, these DC switches 47 and 49 are operated in complimentary fashion, i.e., only one of the DC switches will be open at any arbitrary point in time during operation.

The filter inductor 48 removes unwanted ripple current inherently by high speed modulation of switches 47 and 49. It should be noted that the filter inductor depicted is merely representative of a filter in general (a single inductor would be the simplest form of filter). Alternative embodiments of the filter could include a combination of several passive elements, for example.

Still referring to Fig. 3, the inverter 20 includes the inverter switching circuits 26 for a three-phase AC power supply. Specifically, the inverter inverter switching circuits 26 include three switch pairs, including a phase A switch pair 50a, a phase B switch pair 50b, and a phase C switch pair 50c. Each switch pair 50a, 50b, 50c, includes respectively an upper switch 52a, 52b, 52c, positioned between the +DC rail 37 and its respective phase line, and a lower switch 54a, 54b, 54c, connected between the -DC rail 38 and its respective phase line. As is known in the art, the AC switches 52, 54 are operated in complementary fashion; i.e., only one of the switches in a pair will be open at a point in time during operation of the switching circuit 26.

The AC switches 52 and 54 of the inverter 20 and the DC switches 47, 49 of the DC-DC chopper 21 may include any of a number of different types of active switches, including insulated gate bipolar transistors (IGBT's), bipolar junction transistors (BJT's), field effect transistors (FET's), or Darlington transistors. Each switch 47, 49, 52, and 54 may include only a single transistor, or may include multiple transistors connected in parallel. A freewheeling diode is connected in an inverse parallel relationship with each transistor. The switches 47, 49, 52, and 54 are preferably IGBT's.

Each switch pair 50 is driven by the current regulators 30 and the conventional inverter drive circuits 28 using a power flow waveform for each phase. A conventional filter 56 is provided to smooth the output of the inverter 20, which reduces the high

frequency components inherent in high speed switching. Specifically, the filter 56 removes unwanted harmonic content introduced by high speed modulation of the switch pairs 50a, 50b, 50c. The filter 56 may include reactors and capacitors and, preferably the inductance of the reactors is as large as possible. However, practical concerns such as cost and size usually limit the actual inductance in any installation.

The power flow waveform generator 32 generates AC control waveforms 59a-c, one for each AC phase of the output power. The inputs to the power flow waveform generator 32 include a VAR multiplier M_1 from the reactive power controller 42, a DC bus multiplier M_2 from the DC bus voltage regulator 40, a constant K (if appropriate), and the voltage waveform for each of the three AC phases. In the preferred embodiment, the voltage on each of the phases is transformed to a low level by grid voltage transformers (shown as 44 in Fig. 2). Specifically, the voltage waveform on phase A is transformed to a reference waveform A, the voltage on phase B is transformed to a reference waveform B, and the voltage on phase C is transformed to a reference waveform C. Using these inputs, a control waveform 59 for each phase is generated by the power flow waveform generator 32 in accordance with the algorithms to be described with reference to Figs. 4 and 5 below. Specifically, a Phase A control waveform 59a is generated in the generator 32 and applied through the current regulator 30 and the drive circuit 28 to control the switch pair 50a. Likewise, a Phase B control waveform 59b is generated to control the switch pair 50b, and a Phase C control waveform 59c is generated to control the switch pair 50c. In the preferred embodiment, the power flow control waveforms 59 are produced and applied digitally at a rate between 8 KHz and 16 KHz, which means that the sample period for the control waveforms 59 are between 125 and 62.5 microseconds.

Reference is made to Fig. 4, which is a flowchart of operations within the power flow waveform generator 32 to provide the AC power flow control waveforms 59a-c. In one embodiment, the steps in the flowcharts could be implemented with software and a microprocessor. It should be apparent that other hardware or methods may be used to accomplish the steps described therein.

For purposes of clarity and explanation, Fig. 4 shows only the operations on a single phase. It should be apparent to one skilled in the art that the operations in Fig. 4 occur in parallel for each phase of the output. In a box 60, a reference waveform is obtained. After the reference waveform has been obtained, as in the box 60, it is applied to form an imaginary waveform as illustrated in a box 62. As will be described in more detail, the imaginary waveform may be obtained by rotating the reference waveform by 90°. The imaginary waveform is then multiplied, as illustrated in a box 64, by a multiplier M_1 which is calculated in a manner to be described with reference to Fig. 5. The multiplied imaginary waveform is then added in a box 66.

On the other side of the flowchart, the reference waveform is applied to form the real waveform illustrated in a box 68. The real waveform may be substantially similar to the reference waveform. The real waveform is applied to a box 70, in which it is multiplied by a real multiplier M_2 supplied from the DC bus regulation PI controller 40 discussed in detail below with reference to Figs. 5, 6, and 7. The multiplied real waveform is then added to the multiplied imaginary waveform to obtain a power flow control waveform 59a-c to control the power flow through the inverter 20. Applying the power flow control waveforms 59a-c, as illustrated in a box 72, the switching circuit 26 is controlled to provide a current 26 in each phase that produces the desired power flow.

On the DC portion, the reference current is obtained either directly from an operator interface, or by dividing a power-level input from the operator interface by the sensed battery voltage. The switching circuit is controlled to provide a current through the DC device 22 that produces the desired power flow.

Reference is made to Fig. 5 which is a more detailed illustration of the power flow waveform generator 32. Beginning from the left in Fig. 5, the 3-phase AC reference waveform is applied to a 3- to 2-phase converter 80. The 3- to 2-phase converter 80 converts the 3 phases of the reference waveform to 2 phases in accordance with the following matrix equation:

$$\begin{bmatrix} A_2 \\ B_2 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & \cos(2\pi/3) & \cos(4\pi/3) \\ 0 & \sin(2\pi/3) & \sin(4\pi/3) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{1}$$

where A_2, B_2 are the 2-phase reference quantities and A, B, and C are the 3-phase reference quantities.

The outputs of the 3- to 2-phase converter 80, i.e., the two 2-phase reference waveforms, are provided to two separate processing lines, one that produces and processes an imaginary waveform and another one that produces and processes a real waveform. Specifically, the 2-phase reference waveform is applied to a box 82 in which each phase is multiplied by $e^{j90°}$. Similarly, the 2-phase reference waveform is applied to a box 84 in which each phase is multiplied by $e^{j0°}$ (or 1).

The output of the box 82, a 2-phase imaginary waveform, is then applied to a 2- to 3-phase converter 86 which outputs a 3-phase imaginary waveform. The 2- to 3-phase conversion is accomplished by inverting equation (1):

$$\begin{bmatrix} A^* \\ B^* \\ C^* \end{bmatrix} = \begin{bmatrix} 2/3 & 0 & 1/3 \\ -1/3 & 1/\sqrt{3} & 1/3 \\ -1/3 & 1/\sqrt{3} & 1/3 \end{bmatrix} \begin{bmatrix} A_2 \\ B_2 \\ 0 \end{bmatrix} \tag{2}$$

Similarly, the output of a box 84, a 2-phase real waveform, is applied to a 2- to 3-phase converter 88 to output a 3-phase real waveform. In alternate embodiments, the reference waveform illustrated as an input into the box 80 may be used to form the real waveform at the output of the box 88 without the need for 3- to 2-phase conversion and 2- to 3-phase conversion.

Each phase of the 3-phase imaginary waveform is then multiplied by a VAR multiplier M_1 selected by the reactive power controller 42. The VAR multiplier M_1 has the same value for each phase. In the reactive power controller 42, the VAR multiplier M_1 can be manually selected by an operator who observes the number of VARs at the output and compares them with the VARs desired by the grid 12.

He then adjusts the multiplier M_1 to produce the desired number of VARs. If the utility requires more VARs than the hardware in the line-side inverter 20 can produce, then the VAR multiplier M_1 is limited to a maximum value, at which point it will supply all the VARs that it can. The maximum value is usually determined by the safe current carrying capability of the circuits in the line-side inverter 20. The maximum value may be implemented in software so that the multiplier M_1 cannot exceed that value.

As an alternate to control by an operator, the VAR multiplier M_1 can also be selected automatically by a hierarchical control loop such as a voltage regulator that can be operator controlled to provide a fixed terminal voltage VARs. An error signal may be used in the control loop, to minimize the error between the measured voltage and the desired voltage.

If, instead of controlling the number of VARs, control of the power factor angle is desired, then a value K is selected to specify a predetermined power factor angle. Then, the value K is multiplied by M_2, as illustrated in a box 87. This product is applied to the reactive power controller 42. Thus, if the power factor angle is to be controlled, then the imaginary multiplier M_1 is proportional to the DC bus multiplier M_2 supplied from the DC bus voltage regulator 40 described in detail below.

The DC bus voltage regulator 40 controls the DC bus voltage V_i by importing or exporting power from the utility grid in the amount necessary to maintain a constant predetermined voltage V_i^*. The DC bus voltage regulator 40 receives the actual inverter voltage V_i sensed by the voltage sensor 36 (Fig. 2) and the predetermined voltage V_i^*.

The desired inverter voltage V_i^* is a parameter predetermined by output requirements and device limitations. Preferably, the desired inverter voltage V_i^* is selected to be above the maximum peak-to-peak voltage of the utility grid, but below the maximum voltage rating of the switching devices in the inverter. For example, one predetermined value for V_i^* is 750 volts, which is above the 675 peak-to-peak AC voltage of a 480 volt (rms) utility source, but lower than the maximum voltage rating of commercially-available

switching devices such as a 1400V insulated gate bipolar transistor (IGBT).

Responsive to the actual voltage V_i and the predetermined voltage V_i^*, the DC bus voltage regulator 40 supplies a DC bus multiplier M_2 having a value that maintains the DC side at the predetermined constant voltage V_i^*. The DC bus voltage regulator 40 includes a differencing unit 89 and a proportional plus integral controller 90. In the differencing unit 89, the desired inverter voltage V_i^* is differenced with the actual inverter voltage V_i obtained from the voltage sensor 39. The resulting difference is applied to the proportional plus integral controller 90, whose output supplies the DC bus multiplier M_2.

The DC bus multiplier M_2 is applied to each of the three phase real waveforms from the 2-to-3 phase converter 88 to provide a multiplied real waveform for each phase. Then, the multiplied real waveform for each phase is added respectively to the corresponding phase of the multiplied imaginary waveforms from the upper arm of Fig. 5. The result of this addition operation is the control waveforms 59a, 59b, and 59c. Specifically, the multiplied real waveform for phase A is added to the multiplied imaginary waveform for phase A in order to obtain the control waveform 59a for phase A. Similarly for phase B and phase C, the multiplied real waveform is added to the multiplied imaginary waveform to yield a control waveform 59b and 59c. The control waveforms 59a, 59b, 59c are then applied to the current regulators 30 shown in Figs. 2 and 3, which control the inverter switching circuits 26 through the inverter drive circuits 28.

The DC control unit 41 includes a DC current controller 91 that controls the real power flow by controlling the DC current to and from the DC device 22 with a current control value M_3. One embodiment of the DC control unit 41 will be described with reference to Fig. 7. The DC control unit 41 can be implemented digitally, utilizing a microprocessor to receive inputs, perform calculations, and output a result.

Fig. 7 is a block diagram of the DC control unit 41. The DC current controller 91 receives an input from an operator interface 94,

which receives input information from an operator who specifies a desired real power flow in any convenient measure such as watts. In the conversion unit 95, the desired real power flow is converted in real time to a command current $I_{desired}$ that controls the current flow through the two-quadrant DC-DC chopper 21. The sensed voltage across the DC device 72, V_{DC}, is used together with the desired real power to specify a desired current by the following relation:

$$\frac{\text{Real power desired}}{V_{DC}} = I_{desired} = I^{*}_{DC} \qquad (3)$$

In summary, if the operator input is in terms of desired power, the conversion unit 95 calculates the desired current from the relationship of Equation (3). Of course, the operator could directly provide $I_{desired}$. If the operator input is in terms of desired current, then the conversion unit 95 simply passes this input on to the current controller 91. It will be apparent to one skilled in the art that control of DC current to and from the DC device 22 is equivalent to control of real power through the inverter 20.

The DC current controller 91 is designed to provide a current control value M_3 at its output that will produce the command current $I_{desired}$ to or from the DC device 22. In one implementation, the value for the command current $I_{desired}$ is passed directly through the DC current controller 91. In other words, $I_{desired}$ (= I^{*}_{DC}) is used directly as the current control value M_3 to control the currents to provide the DC device current control waveform. Use of this current control value is illustrated in Fig. 9 and discussed therewith.

Reference is briefly made to Figs. 2 and 3 in conjunction with Figs. 5 and 7. Because the two quadrant DC-DC chopper 21 is controlled to supply a specific current $I_{desired}$, current will be drawn through the inverter 20 in an amount necessary to meet this need. At the same time, the DC side of the inverter is controlled by the DC voltage bus regulator 40 at a constant voltage V_i^{*}. Therefore, the combined effect of the two controllers (i.e. the DC bus voltage regulator 40 and the DC control unit 41) is that, by maintaining the constant voltage on the DC side, the DC bus regulator 40 operates to draw the current through the

inverter 20 in the amount necessary to meet the specified current needs of the DC device 22 via the two quadrant DC-DC chopper 21.

In embodiments in which the DC device 22 is a battery or other device that can both store and supply electrical energy, a charge/discharge controller 92 receives the current control value M_3. Additional inputs into the charge/discharge controller include V_{DC}, (the voltage sensed across the DC device 22) and predetermined values for a high voltage V_H and a low voltage V_L. These predetermined values specify an operating range for the DC device 22. The values chosen for the voltages V_H and V_L are highly dependent upon the particular DC device 22 in a particular application. The value V_L, for instance, could be a voltage that determines when the DC device 22 is fully discharged so that it can no longer supply power. The maximum voltage, V_H, is the voltage indicating that the DC device 22 is fully charged. The value V_H could be used for determining when to stop charging the DC device 22. Depending upon the actual charge on the DC device 22, as measured by V_{DC}, the charge controller 92 adjusts the real power multiplier M_3. For example, when a fully charged state is reached, the charge controller 92 can set M_3 to zero. Operation of one embodiment of the charge controller 92 is described further with reference to Fig. 6.

Reference is now made to Fig. 6 which illustrates one method of implementing the charge controller 92. In a box 94, an operator inputs the mode and amount of either the DC current or the real power flow. As described above with reference to Fig. 7, the amount of real power flow may be specified by the operator in watts, and then converted to the command current $I_{desired}$ in a box 95 (Fig. 7) by dividing it by V_{DC}. The mode is specified by a "positive" or "negative" designation. The modes are defined, for purposes of illustration, as a charge mode for a real power flow towards the DC energy device ($I_{desired} > 0$), an idle mode for no power flow ($I_{desired} = 0$), and a discharge mode for a power flow from the DC energy storage device to the AC utility grid 12 ($I_{desired} < 0$). Exiting from the input box 94, a decision is made, dependent upon three conditions: whether the idle mode has been selected as illustrated in a decision 96, whether the

charge mode has been selected as illustrated in a decision 98, or whether a discharge mode has been selected as illustrated in a decision 100. If the idle mode has been chosen, then, from the box 96, the operation moves to a decision 102 which continues the idle loop until the mode has changed to either a charge mode or a discharge mode.

If the charge mode has been selected then operation exits from the box 98 into a charge loop. In the charge loop, the charge on the DC device 22 is measured, and a decision 104 is made based upon the charge of the DC device 22. If the DC device 22 is fully charged, then operation returns to the input box 94 to wait for another operator input. However if the DC device 22 is not fully charged then operation moves to an operation box 106 which supplies the desired current to charge the DC device 22. A decision 108 allows the operator to exit the charge loop. Until the mode changes, operation loops through the charge loop including the charge decision 104, the operation box 106, and the mode decision 108. If the mode changes, then operation returns to the operator input box 94. Thus, the charge loop continues until the DC device 22 is fully charged as illustrated in the decision 104, or until the mode changes as illustrated in the box 108. If the DC device 22 is fully charged, the charge controller can supply a value to the adder to counter $M_{desired}$, so that $M_3 = 0$.

In the decision 100, a supply mode may be chosen to supply energy to the utility grid 12. If the supply mode is chosen, then the supply loop is entered. The charge on the DC device 22 is monitored, and if the DC device 22 is fully discharged, then it can of course supply no further energy and operation returns to the input box 94. However if energy is available (i.e., if the DC device 22 has energy to be supplied) then operation moves to the box 112 in which the desired current is supplied to the utility grid 12. Next, as illustrated in the decision 114, when the mode changes then operation returns to the input 94. As long as the mode does not change then the supply loop continues to supply the desired current to the utility grid. This supply loop continues until either the DC device 22 is fully discharged as illustrated in the decision 110, or until the operator changes the mode as illustrated in the box 114. If the DC device 22 is fully discharged, then

the charge controller can supply a value to the adder to balance $M_{desired}$, so that $M_3 = 0$ and no real power will flow.

Fig. 6 illustrates only one embodiment of a charge controller 92. It will be apparent to one skilled in the art that other implementations of the charge controller may be developed to control charging the battery. For example, instead of allowing the full specified real power flow, another charge controller may increase or decrease the actual real power flow dependent upon V_{sensed}. It will also be apparent to one skilled in the art that the controller may be adapted to DC sources of energy such as photovoltaic cells and fuel cells by eliminating the charge mode.

One simple method of current control is illustrated in Fig. 8, which is a delta modulator current regulator 118 that applies the 3-phase AC line currents i_A^*, i_B^*, i_C^* specified by the control waveforms 59a, 59b, 59c and the DC current i_D^*. The delta modulator current regulator 118 periodically compares each desired line current i_A^*, i_B^*, i_C^* or DC device current i_{DC}^*, with the corresponding actual line current i_A, i_B, i_C, and DC device current i_{DC}, sensed by the respective current sensors 120a, 120b, 120c, and 39 (Fig. 3). The current sensors 120a-c are positioned to sense the line currents from each of the switch pairs 50a-c. The current sensor 39 is positioned to sensor the current through the DC device 22.

A current comparison is accomplished using a compare device 122 for each of the lines. In the preferred embodiment, current comparisons are performed at a rate between 8 and 16 KHz, which is equivalent to a sample period between 125 and 62.5 microseconds.

For each sample period, if the desired line current for a phase is greater than the actual line current, then the respective upper switching device 52 or 47 is switched on and the lower switching device 54 or 49 switched off, otherwise, the upper device 52 or 47 is switched off and the lower device 54 or 49 is switched on.

The compare devices 122 provide PWM (Pulse Width Modulation) commutation signals, D_A, $\overline{D}_A$, D_B, $\overline{D}_B$, D_C, $\overline{D}_C$, and D_D, $\overline{D}$ $)_D$ that are applied to the inverter drive circuits 28 to accomplish the desired switching. The inverter drive circuits 28 preferably include

conventional transistors and additional circuitry necessary to drive the gates of the respective switches 47, 52, 49, and 54, which are IGBT's in the preferred embodiment, in response to the on or off signal specified by the PWM commutation signals. For each sample period, a switch state is specified by the PWM commutation signals. The switch state so selected remains in effect until the next sample period, at which time the comparisons are repeated with updated actual and desired values. In alternate embodiments, other conventional PWM methods can be used.

Reference is now made to Fig. 9, which is a block diagram illustrating two separate DC devices coupled to a common DC bus 200. The common DC bus is coupled on the DC side to the inverter 20 and the AC electric power grid illustrated and discussed with reference to Fig. 1, for example.

The DC bus 200 is coupled to a battery 206 by a two quadrant DC-DC chopper 21a. The DC bus 200 is also coupled to photovoltaic or fuel cells 210 through the two quadrant DC-DC chopper 21b. The photovoltaic or fuel cells 210 may comprise any of a plurality of DC generating cells. The two quadrant DC-DC choppers 21a-b are constructed and controlled in the matter described elsewhere, and the DC bus 200 may comprise a capacitor for short term energy storage across the bus.

Although only two DC devices have been illustrated coupled to the DC bus 200, any of a plurality of other DC devices could also be coupled to the DC bus 200. For example, additional batteries may be coupled to the DC bus 200 by an additional two quadrant DC-DC chopper. The effect of the two quadrant DC-DC choppers is to isolate the DC bus 200 from the particular DC device, thereby allowing any of a plurality of DC devices with different output voltage characteristics to be coupled to the DC bus 200.

The invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiment is to be considered in all respects only as illustrative and not restrictive and the scope of the invention is, therefore, indicated by the appended claims rather than by the

foregoing descriptions. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

CLAIMS

WHAT IS CLAIMED IS:

1. A method for bidirectionally controlling a flow of power in a inverter and a DC-DC chopper coupled between an AC utility grid and a DC device, comprising the steps of:

selecting a real power flow in direction and amount;

controlling current flow through the DC-DC chopper responsive to a sensed DC voltage on said DC device to provide said real power flow; and

controlling said PWM inverter, responsive to a sensed voltage on a DC side of said PWM inverter, to maintain a predetermined voltage on said DC side.

2. The method of claim 1 wherein the AC utility grid has a plurality of phase lines, further comprising for each of said phase lines the steps of:

forming a reference waveform from a voltage waveform the AC utility grid;

calculating a DC bus multiplier responsive to the command real power flow and the sensed parameter;

multiplying the reference waveform by the DC bus multiplier to provide a multiplied waveform; and

applying the multiplied waveform to control the instantaneous current flow through the inverter, therefore controlling the power flow through the inverter.

3. The method of claim 1 further comprising the steps of:

monitoring a sensed level of the DC device;

comparing the sensed charge level with a predetermined maximum charge and a predetermined minimum charge;

if the selected real power flow is in a direction toward the load, then allowing current to flow through the inverter only if the sensed charge does not exceed the maximum charge; and

if the selected real power flow is in a direction toward the AC utility grid, then allowing current to flow through the inverter only if the sensed charge exceeds the minimum charge.

4. A DC electrical energy apparatus for converting electrical energy between AC on an AC electric power supply and DC in a DC device, said AC electric power supply having a plurality of phase lines, said DC electrical energy apparatus comprising:

a DC device;

a DC-DC chopper inverter coupled to the DC device for bidirectionally regulating instantaneous current flow;

a real power controller coupled to control the DC-DC chopper inverter to provide a predetermined DC current flow responsive to a sensed DC current flow;

a PWM inverter having a DC side coupled to the DC-DC chopper inverter and an AC side coupled to the AC electric power grid; and

a DC bus voltage regulator coupled to the PWM inverter for maintaining a predetermined voltage level responsive to a sensed voltage on said DC side.

5. The DC electrical energy apparatus of claim 4 further comprising a reactive power controller coupled to the PWM inverter to supply a selected reactive power to the AC electric power supply, said selected reactive power being substantially independent of the amount of real power flowing between the AC electric power grid and the DC side of the PWM inverter.

6. The DC electrical energy apparatus of claim 4 wherein the inverter control unit includes:

a power flow waveform generator coupled to the DC bus voltage regulator; and

a current regulator coupled to the power flow waveform generator, including a delta modulator current regulator.

7. The DC electrical energy apparatus of claim 4 further comprising:

an imaginary waveform circuit for rotating the reference waveform by 90° to form an imaginary waveform;

a multiplying circuit for multiplying the imaginary waveform by the imaginary multiplier; and

an adding circuit for adding the multiplied real waveform and the multiplied imaginary waveform to provide the power flow control waveform.

8. The DC electrical energy apparatus of claim 4 further comprising:

a circuit for forming a reference waveform from the voltage waveform of the utility supply;

a circuit for applying the reference waveform to form a real waveform;

monitoring means for monitoring a current flow through the inverter;

a current flow selection circuit for selecting a desired current flow;

a determining circuit, responsive to the monitoring means and the selection means, for determining a real multiplier;

a circuit for multiplying the real multiplier by the real waveform to form a multiplied real waveform for controlling the direction and amount of real power flow through the inverter; and

a circuit for including the multiplied real waveform in the power flow control waveform.

9. The DC electrical energy apparatus of claim 8 further comprising:

an imaginary waveform circuit for rotating the reference waveform by 90° to form an imaginary waveform;

a circuit for multiplying the imaginary waveform by the imaginary multiplier; and

an adding circuit for adding the multiplied real waveform and the multiplied imaginary waveform to provide the power flow control waveform.

10. A DC electrical energy apparatus for converting electrical energy between AC on an AC electric power grid and DC on a DC device, and supplying a selectable number of VARs of reactive power to the AC electric power grid, said AC electric power grid having a plurality of phase lines, said DC electrical energy apparatus comprising:

a PWM inverter including

a plurality of switch pairs coupled to said plurality of phase lines for regulating the instantaneous current flow, and

a DC bus on a DC side of said PWM inverter including a first DC rail and a second DC rail;

a DC-DC chopper inverter coupled to said DC bus including a first switch coupled to said first DC rail;

a filter inductor coupled to said first switch;

a second switch coupled between said first switch and said second DC rail;

a DC device coupled between said inductor and said second switch; and

an inverter control unit for controlling the PWM inverter switch pairs by pulse-width modulation of the

instantaneous current flow through the inverter to provide a real and reactive power flow, including:

a power flow waveform generator for forming a power flow control waveform having a real component and an imaginary component,

a DC bus voltage regulator for providing a power flow in direction and amount to maintain a predetermined voltage on the DC side responsive to a sensed voltage on the DC side, and

a reactive power controller responsive to a predetermined reactive power amount for controlling the imaginary component of the power flow control waveform to supply said predetermined reactive power amount to the utility grid.

11. The DC electrical energy apparatus of claim 10, wherein the reactive power controlled by the reactive power controller comprises a constant number of VARs, said selected constant number of VARs being substantially independent of the amount of real power provided to the AC electric power grid.

12. The DC electrical energy apparatus of claim 10, further comprising:

a plurality of waveform sensors for sensing the voltage waveforms of each of the phase lines of the polyphase electric power supply, said voltage waveform defining a reference waveform for forming the real component and the imaginary component of the power flow control waveform;

a current regulator coupled to said waveform sensors; and

a drive circuit coupled between said current regulator and said PWM inverter for switching said switch pairs in accordance with the power flow control waveform.

13. The DC electrical energy apparatus of claim 12 wherein the current regulator comprises a delta modulator current regulator.

14. The DC electrical energy apparatus of claim 12 wherein the power flow waveform generator includes:

means for rotating the reference waveform by 90° to form an imaginary waveform; and

means for multiplying the imaginary waveform by a first multiplier selected by the reactive power control means to provide a predetermined number of VARs.

15. The DC electrical energy apparatus of claim 14 wherein the power flow waveform generator further includes:

means for forming a real waveform from the reference waveform; and

means for multiplying the real waveform by a second multiplier selected by the real power control means to provide a selected real power flow.

16. The DC electrical energy apparatus of claim 15 wherein the first multiplier is selected proportional to the second multiplier to provide an approximately constant power factor angle.

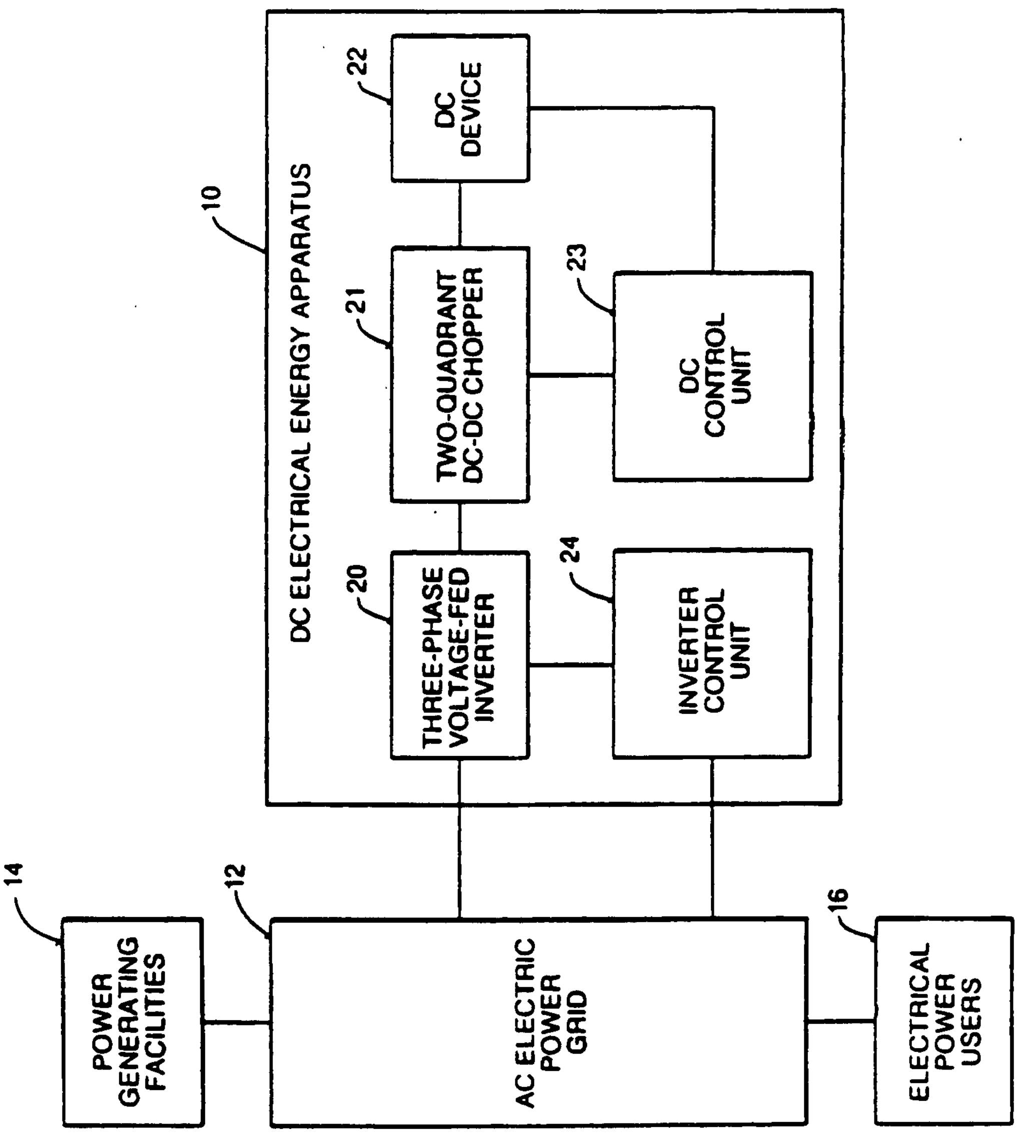

DC ELECTRICAL ENERGY APPARATUS
10
DC DEVICE
22
TWO-QUADRANT DC-DC CHOPPER
21
DC CONTROL UNIT
23
THREE-PHASE VOLTAGE-FED INVERTER
20
INVERTER CONTROL UNIT
24
POWER GENERATING FACILITIES
14
AC ELECTRIC POWER GRID
12
ELECTRICAL POWER USERS
16

FIG_1

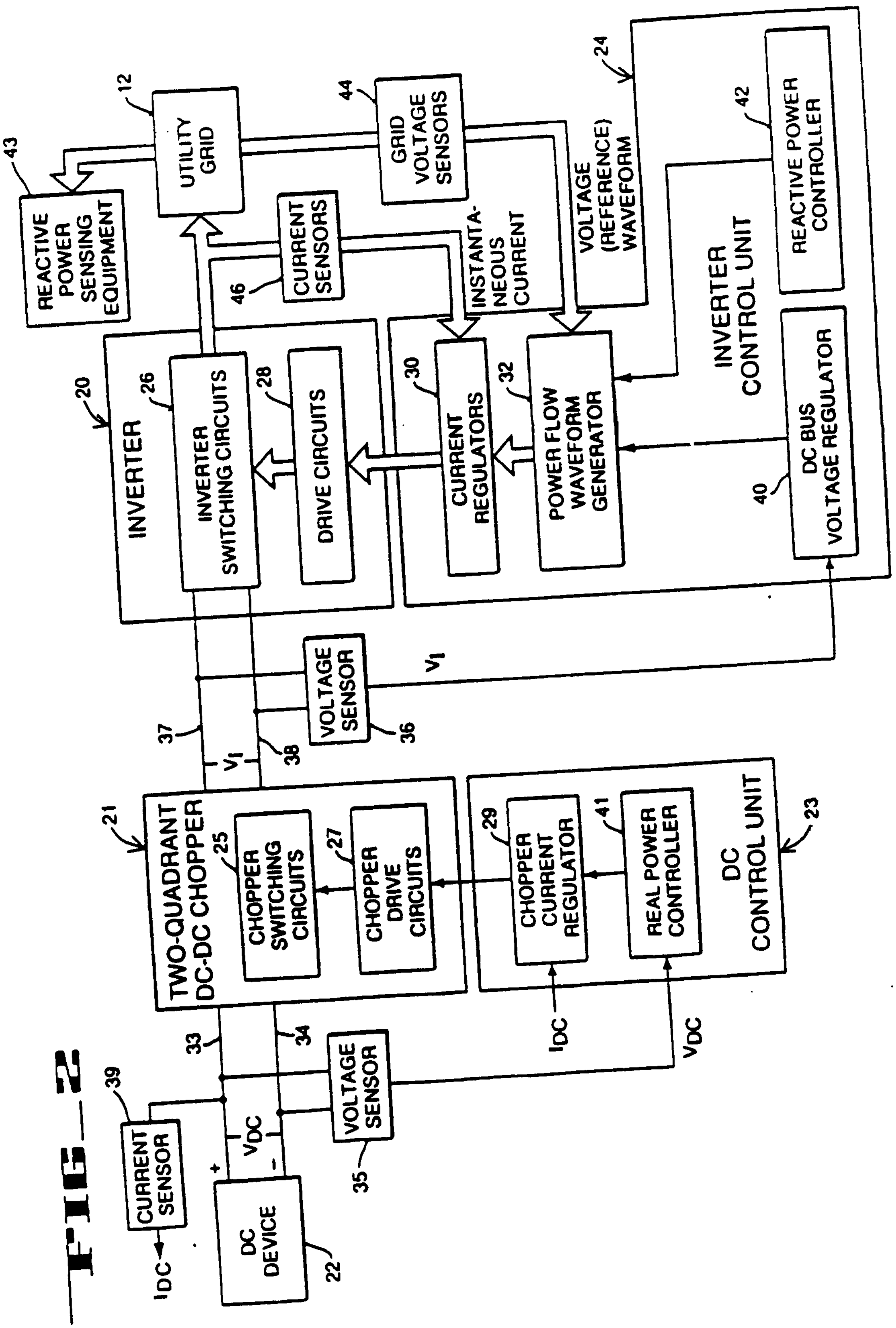

REACTIVE POWER SENSING EQUIPMENT
43
UTILITY GRID
12
GRID VOLTAGE SENSORS
44
24
CURRENT SENSORS
46
INSTANTANEOUS CURRENT
VOLTAGE (REFERENCE) WAVEFORM
REACTIVE POWER CONTROLLER
42
INVERTER CONTROL UNIT
INVERTER
20
INVERTER SWITCHING CIRCUITS
26
DRIVE CIRCUITS
28
CURRENT REGULATORS
30
POWER FLOW WAVEFORM GENERATOR
32
DC BUS VOLTAGE REGULATOR
40
VOLTAGE SENSOR
36
37
38
V_I
TWO-QUADRANT DC-DC CHOPPER
21
CHOPPER SWITCHING CIRCUITS
25
CHOPPER DRIVE CIRCUITS
27
CHOPPER CURRENT REGULATOR
29
REAL POWER CONTROLLER
41
DC CONTROL UNIT
23
I_{DC}
V_{DC}
33
34
VOLTAGE SENSOR
35
CURRENT SENSOR
39
DC DEVICE
22
+
-

FIG_2

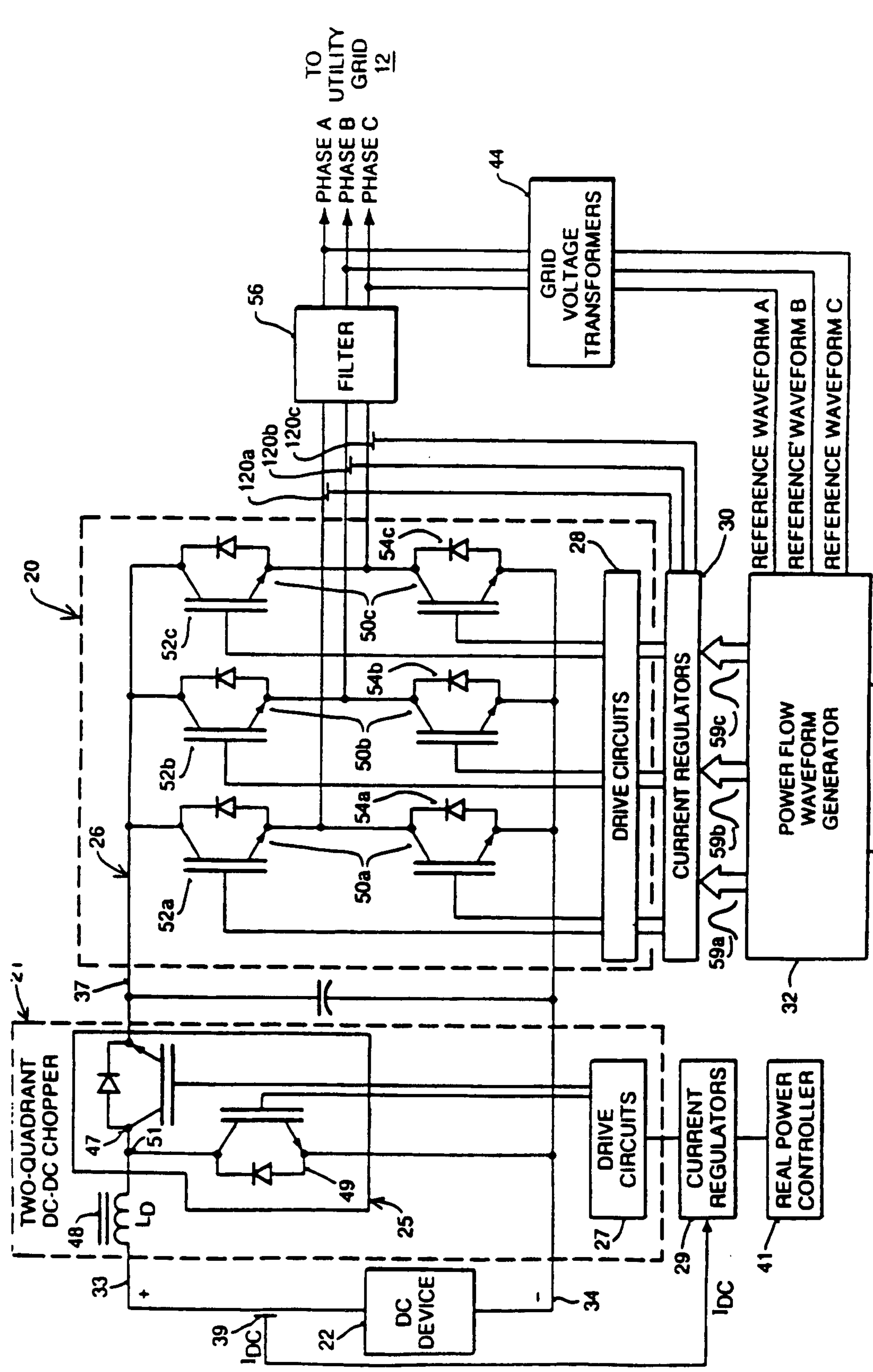

TO UTILITY GRID 12
PHASE A
PHASE B
PHASE C
GRID VOLTAGE TRANSFORMERS
44
FILTER
56
120a
120b
120c
REFERENCE WAVEFORM A
REFERENCE WAVEFORM B
REFERENCE WAVEFORM C
20
26
28
30
52a
52b
52c
50a
50b
50c
54a
54b
54c
DRIVE CIRCUITS
CURRENT REGULATORS
59a
59b
59c
POWER FLOW WAVEFORM GENERATOR
32
VAR MULTIPLIER M_1
DC BUS MULTIPLIER M_2
21
37
TWO-QUADRANT DC-DC CHOPPER
47
51
49
25
48
L_D
DRIVE CIRCUITS
27
CURRENT REGULATORS
29
REAL POWER CONTROLLER
41
33
34
+
-
DC DEVICE
22
39
I_{DC}
I_{DC}

FIG_3

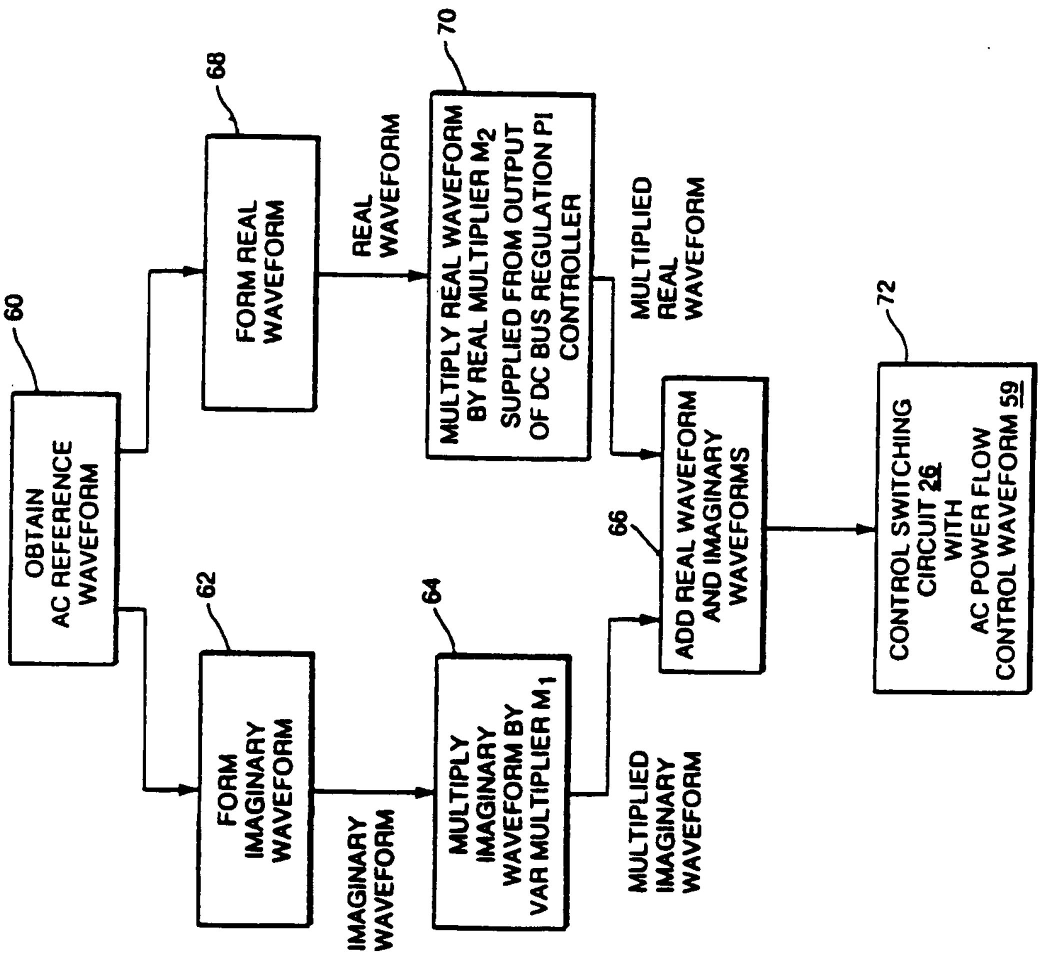

OBTAIN AC REFERENCE WAVEFORM
60
FORM REAL WAVEFORM
68
REAL WAVEFORM
MULTIPLY REAL WAVEFORM BY REAL MULTIPLIER M2 SUPPLIED FROM OUTPUT OF DC BUS REGULATION PI CONTROLLER
70
MULTIPLIED REAL WAVEFORM
FORM IMAGINARY WAVEFORM
62
IMAGINARY WAVEFORM
MULTIPLY IMAGINARY WAVEFORM BY VAR MULTIPLIER M1
64
MULTIPLIED IMAGINARY WAVEFORM
ADD REAL WAVEFORM AND IMAGINARY WAVEFORMS
66
CONTROL SWITCHING CIRCUIT 26 WITH AC POWER FLOW CONTROL WAVEFORM 59
72

FIG_4

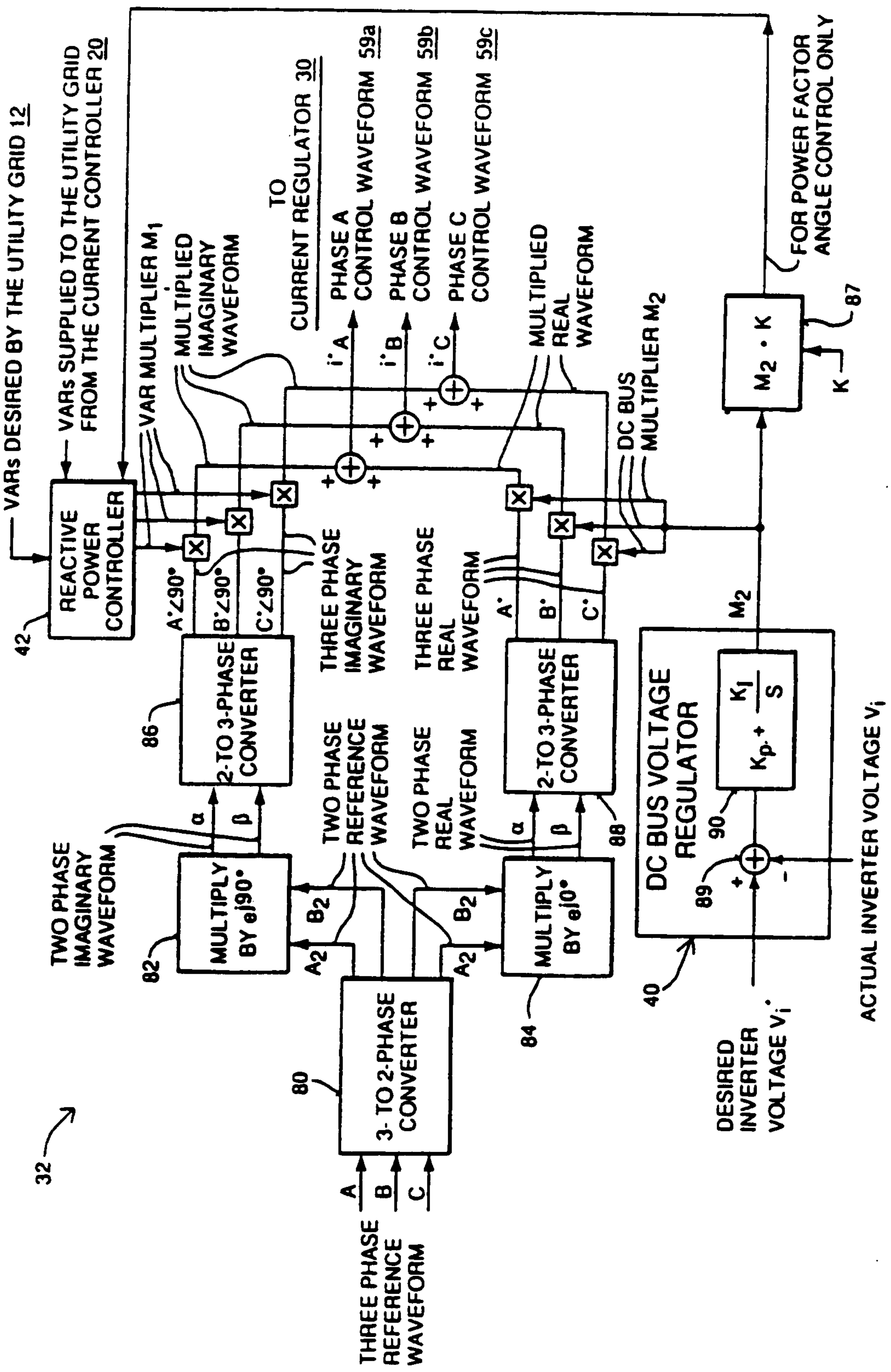

VARs DESIRED BY THE UTILITY GRID 12
VARs SUPPLIED TO THE UTILITY GRID FROM THE CURRENT CONTROLLER 20
VAR MULTIPLIER M_1
MULTIPLIED IMAGINARY WAVEFORM
TO CURRENT REGULATOR 30
PHASE A CONTROL WAVEFORM 59a
PHASE B CONTROL WAVEFORM 59b
PHASE C CONTROL WAVEFORM 59c
MULTIPLIED REAL WAVEFORM
DC BUS MULTIPLIER M_2
FOR POWER FACTOR ANGLE CONTROL ONLY
87
$M_2 \cdot K$
K
42
REACTIVE POWER CONTROLLER
A'∠90°
B'∠90°
C'∠90°
i'_A
i'_B
i'_C
THREE PHASE IMAGINARY WAVEFORM
THREE PHASE REAL WAVEFORM
A'
B'
C'
M_2
86
2-TO 3-PHASE CONVERTER
88
2-TO 3-PHASE CONVERTER
DC BUS VOLTAGE REGULATOR
$K_p + \frac{K_I}{S}$
90
89
ACTUAL INVERTER VOLTAGE V_i
TWO PHASE IMAGINARY WAVEFORM
TWO PHASE REFERENCE WAVEFORM
TWO PHASE REAL WAVEFORM
α
β
82
MULTIPLY BY ej90°
84
MULTIPLY BY ej0°
A_2
B_2
40
DESIRED INVERTER VOLTAGE V_i^*
80
3- TO 2-PHASE CONVERTER
32
A
B
C
THREE PHASE REFERENCE WAVEFORM

FIG_5

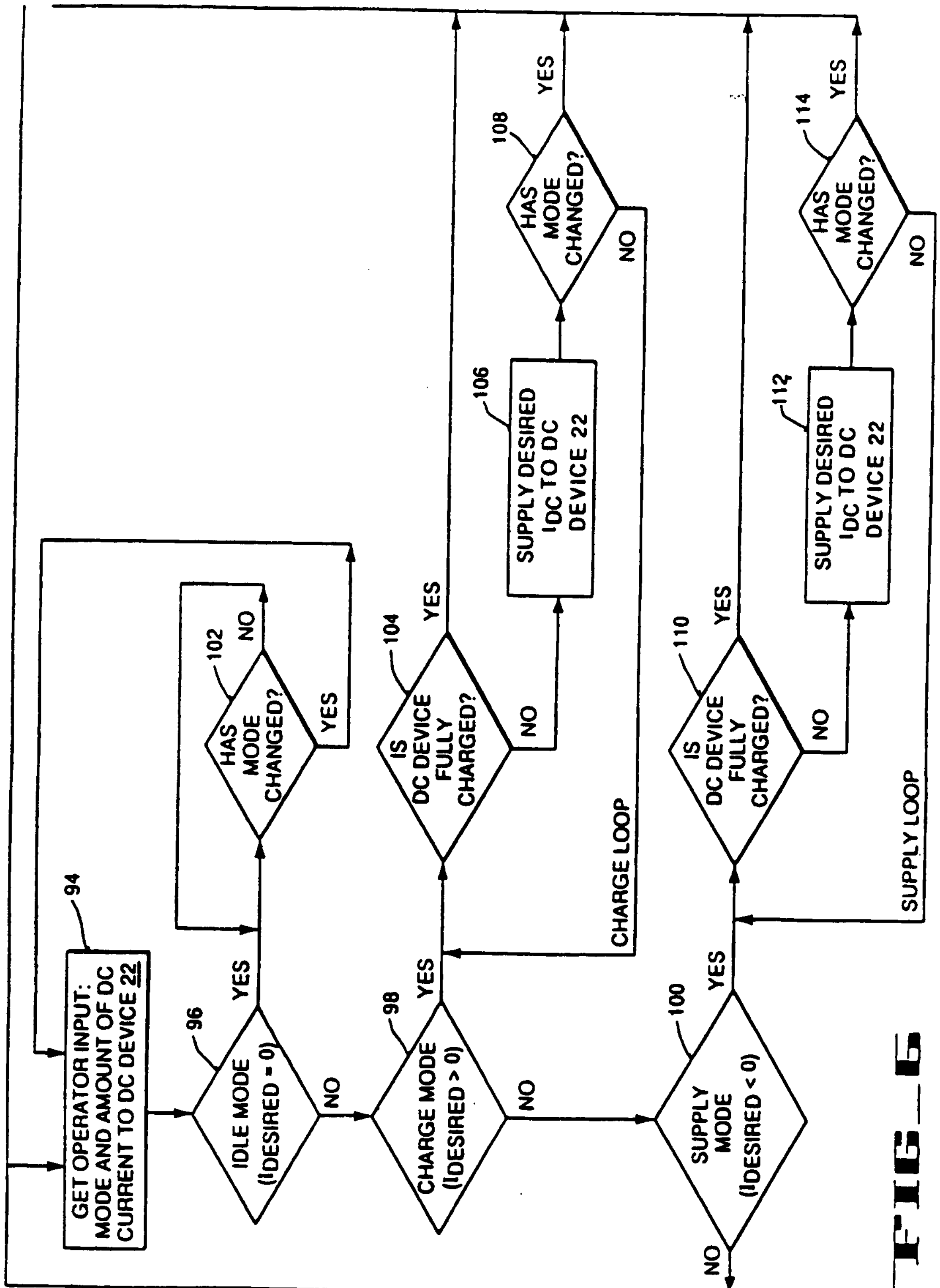
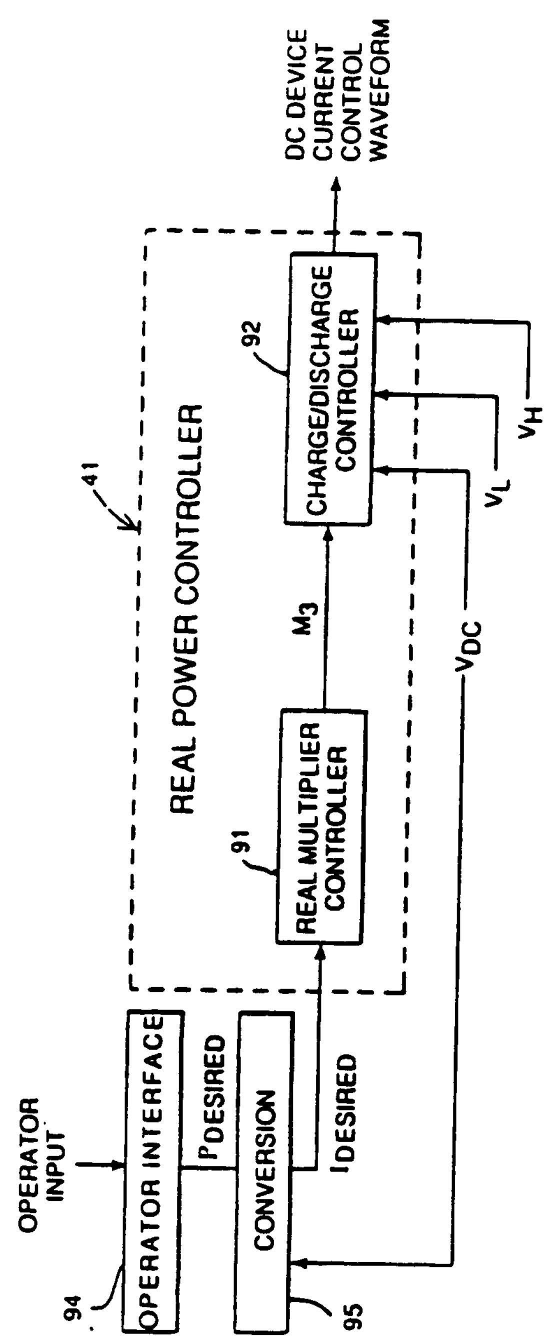
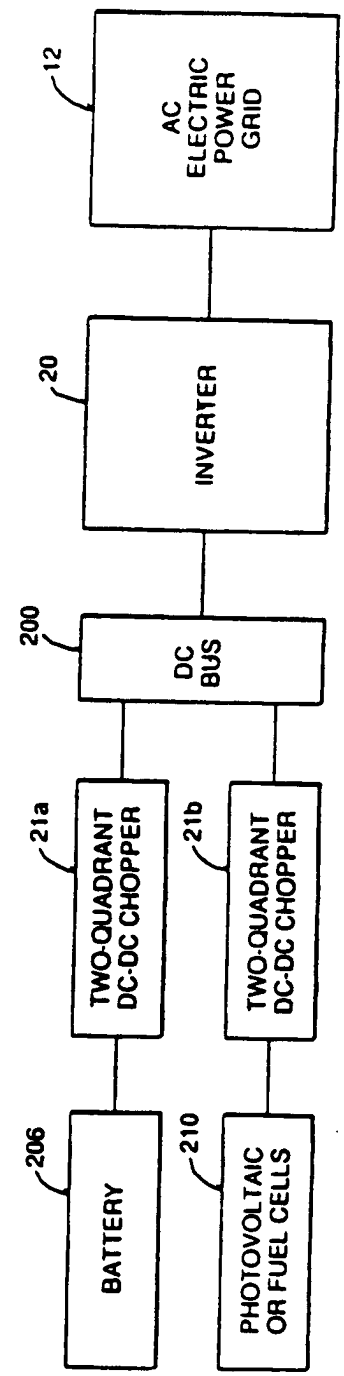

GET OPERATOR INPUT: MODE AND AMOUNT OF DC CURRENT TO DC DEVICE 22
94
IDLE MODE ($I_{DESIRED} = 0$)
96
CHARGE MODE ($I_{DESIRED} > 0$)
98
SUPPLY MODE ($I_{DESIRED} < 0$)
100
HAS MODE CHANGED?
102
IS DC DEVICE FULLY CHARGED?
104
SUPPLY DESIRED I_{DC} TO DC DEVICE 22
106
HAS MODE CHANGED?
108
IS DC DEVICE FULLY CHARGED?
110
SUPPLY DESIRED I_{DC} TO DC DEVICE 22
112
HAS MODE CHANGED?
114
CHARGE LOOP
SUPPLY LOOP
YES
NO

FIG_6



OPERATOR INPUT
OPERATOR INTERFACE
94
$P_{DESIRED}$
CONVERSION
95
$I_{DESIRED}$
REAL POWER CONTROLLER
41
REAL MULTIPLIER CONTROLLER
91
M_3
CHARGE/DISCHARGE CONTROLLER
92
V_{DC}
V_L
V_H
DC DEVICE CURRENT CONTROL WAVEFORM

FIG_7



BATTERY
206
PHOTOVOLTAIC OR FUEL CELLS
210
TWO-QUADRANT DC-DC CHOPPER
21a
TWO-QUADRANT DC-DC CHOPPER
21b
DC BUS
200
INVERTER
20
AC ELECTRIC POWER GRID
12

FIG_9

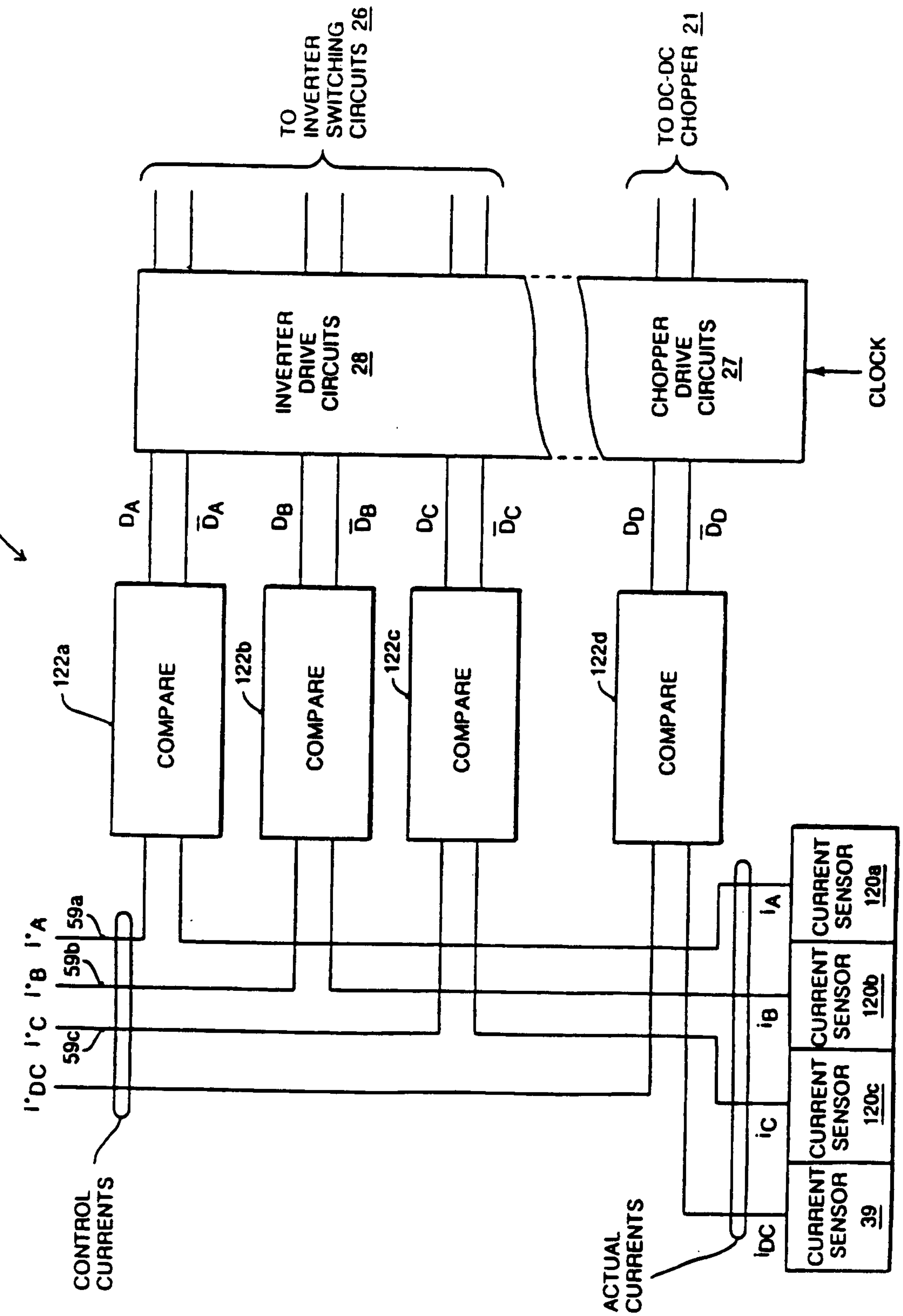

TO INVERTER SWITCHING CIRCUITS 26
TO DC-DC CHOPPER 21
INVERTER DRIVE CIRCUITS 28
CHOPPER DRIVE CIRCUITS 27
CLOCK
118
D_A
$\overline{D}_A$
D_B
$\overline{D}_B$
D_C
$\overline{D}_C$
D_D
$\overline{D}_D$
122a
122b
122c
122d
COMPARE
COMPARE
COMPARE
COMPARE
I'_A
I'_B
I'_C
I'_{DC}
59a
59b
59c
CONTROL CURRENTS
ACTUAL CURRENTS
i_A
i_B
i_C
i_{DC}
CURRENT SENSOR 120a
CURRENT SENSOR 120b
CURRENT SENSOR 120c
CURRENT SENSOR 39

FIG_8